Planar Rotary Motor using Ultrasonic Horns

Stewart Sherrit, Xiaoqi Bao, Mircea Badescu, Zensheu Chang, Daniel Geiyer, Phillip Allen, Patrick Ostlund, Yoseph Bar-Cohen

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099

ABSTRACT

One of the first piezoelectric motor designs with significant rotational speeds was outlined by Barth. This device used extensional piezoelectric elements to produce a time varying force at a distance *r* from the center of a centrally supported disk. These extensional actuators produced micro-steps at a high frequency with the end result being macroscopic rotation of the disk and high torque. The rotation direction is controlled by the choice of the actuators and the direction of the extension about the rotor center. A recent advancement in producing pre-stressed power ultrasonic horns using flexures allows for the development of high torque ultrasonic motors based on the Barth's idea that can be fabricated in a 2D plate or in more complicated 3D structures. In addition to the pre-stress flexures the design also allows for the use of flexures to produce the rotor/horn normal force. The torque can be controlled by the number of actuators in the plane and the amplitude of the normal force. This paper will present analytical and experimental results obtained from testing prototype planar motors.

KEYWORD: Piezoelectric, piezoelectric horn transducers, planar structures, rotary motion, ultrasonic impacts.

1. INTRODUCTION

Ultrasonic motors based on piezoelectric actuation have been available for some time[1,2,3]. The mode of operation, (quasistatic or resonant), type of motion (rotary or linear) and the shape of actuation element (beam, rod, disk, etc.) can be used to classify piezoelectric motors. Despite these distinctions, the fundamental principles of solid-state actuation are common to all of these devices. Each of these motor designs uses microscopic material deformations (usually associated with piezoelectric materials) which are amplified through either quasi-static or dynamic/resonant means.

Motors are an important element of most mechanisms. Most actuators are based on electromagnetic rotary motors, such as DC, AC, brush and brushless, etc. Generally, these types of motors compromise speed, which can be as high as many thousands of RPM, for torque using speed-reducing gears. The use of gear adds mass, volume and complexity as well as reduces the system reliability due the increase in number of the system components. The miniaturization of conventional electromagnetic motors is limited by manufacturing constraints and loss of performance efficiency. Potentially, rotary motors that are actuated by piezoelectric ceramics can offer an effective alternative for miniature-mechanisms Hollerbach[4]. These emerging motor technologies provide high torque density at low speed, high holding torque[5] , zero-backlash, simple construction, quiet operation and have a fast response times. They can also be made in annular through hole shapes for optical applications, electronic packaging and wiring through the center.

One of the first piezoelectric motor designs with significant rotational speeds discussed by Sashida**Error! Bookmark not defined.** and originally published by Barth[6] is what is now known as the Barth Motor[7,8] . This device used extensional piezoelectric elements to produce a time varying force at a distance r from the center of a centrally supported disk as is shown in Figure 1. These microsteps occur at a high frequency with the end result being macroscopic rotation of the rotor. The rotation direction is controlled by the choice of the actuators. This motor was reported to produce a significant torque however a measureable wear was noted during the motor operation and characterization. Another feature of these motors is they can be manufactured in a plane to produced compact low profile rotary motors.

In order to investigate these horn motors and in addition to investigate whether the piezoelectric ceramic could be pre-stressed using flexures we designed a set of horns that could be used to drive a rotor to do useful work. In addition we investigated the use of rapid prototyping in the manufacture of these horns. The monolithic horns were manufactured using Titanium (Ti-6Al-4V) and an electron beam melting/manufacturing process (EBM) by CALRAM Inc. In the

EBM process the titanium parts can be made to an accuracy of about 0.4 mm with comparable strengths to as cast and wrought materials[9]. The part quality is such that they are now used in both the aerospace and in medical implant fields. The EBM manufacturing approach is useful for small production runs. If larger production and cheaper cost per part is required one could use investment casting tree approach[10] where it is also possible to co-cast stainless steel and titanium. A CAD model and the horns as produced are shown in Figure 2.

The piezoelectric stacks were purchased from Piezomechanik Gmbh. The bi-polar stacks were nominally 25.4 mm OD. and 9.33 mm thick. The impedance spectrum of the first length extensional mode for these stacks is shown in Figure 3. An analysis of the small signal resonance data of the bare stack gave an effective piezoelectric constant of 480 pC/N for the material and a capacitance of –261 nF. The coupling was determined to be k_{33} =0.56 and the elastic compliance at constant field in the 33 direction was $5.4\mathrm{x}10^{-11}$ m^2/N. The mechanical Q was in the 40 - 80 range.

The prototype horn motor and the CAD assemble are shown in Figure 4. Initial testing of the motor with one horn demonstrated a rotor speed of 15 RPM with a torque of approximately 0.3 N-m could be produced. The torque was determined by hanging a mass around the shaft, then measuring the constant rate at which the mass was lifted against gravity.

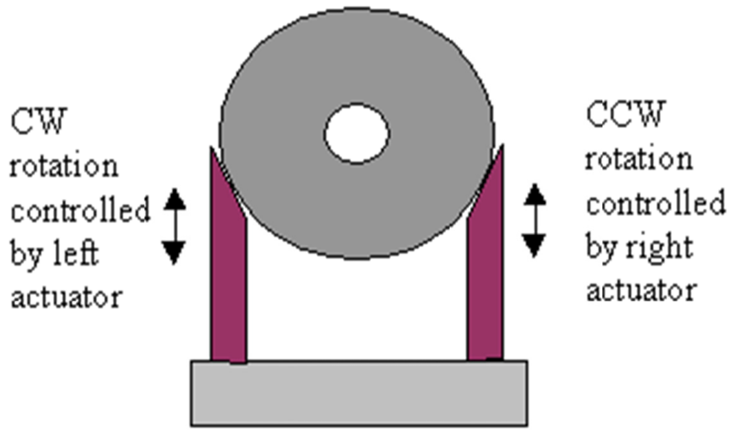


FIGURE 1: Schematic diagrams of a Barth Motor[6]

FIGURE 2: CAD model and photograph of the finished horn. Critical surfaces were machined after rapid prototyping. The flexure is opened and the piezoelectric is pre-stress to a level of 25 MPa.

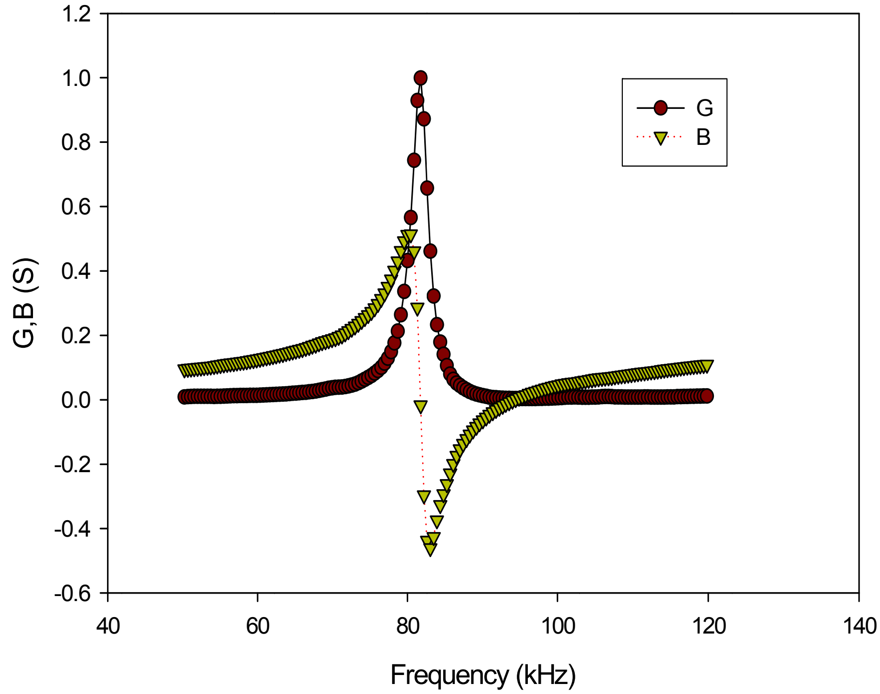


FIGURE 3. Impedance spectra of the bare Piezomechanik Gmbh bipolar stack.

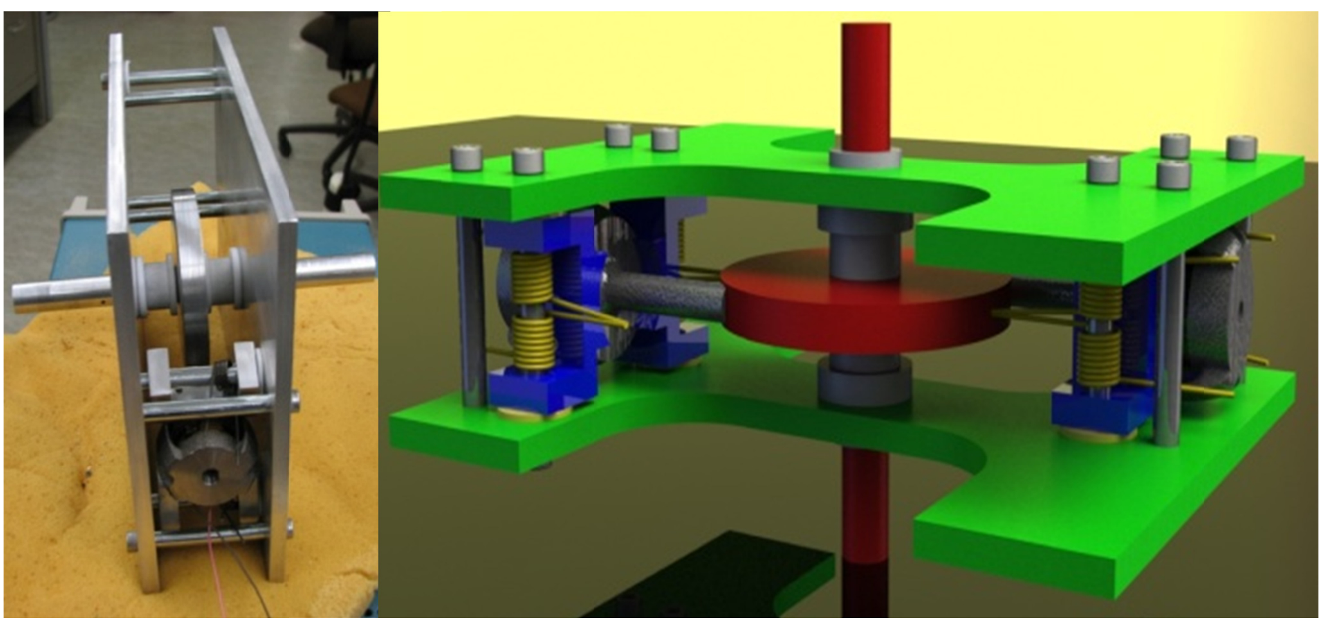


FIGURE 4. A CAD rendering and a photograph of an example of a Barth motor produced by mounting a flexure ultrasonic horn against a rotor. The high frequency horn impacts the rotor and produces a rotary motion.

2. PLANAR DESIGNS

In order to take advantage of the pre-stress flexures we have designed a series of motors in planar structures which can be machined by standard fabrication techniques including milling and electric discharge machining (EDM). The first concept we developed for producing rotary motion based on the Barth concept using a series of ultrasonic horns driving a rotor in one direction (See Figure 5). The unique feature of these motors is that they can be designed in a monolithic planar structure as shown in Figure 5. The design shown in Figure 5 is a unidirectional motor, which is driven by 8 horn actuators, that rotates in the clockwise direction. There are two sets of flexures. The flexures around the piezoelectric material are pre-stress flexures and they pre-load the piezoelectric disks to maintain the piezoelectric stacks under compression while being operated and electric field is applied. The other set of flexures are mounting flexures that are attached to the horn at the nodal point and can be designed to generate a normal force between the horn tip and the rotor so that to first order it operates independently and compensates for the wear between the horn and the rotor.

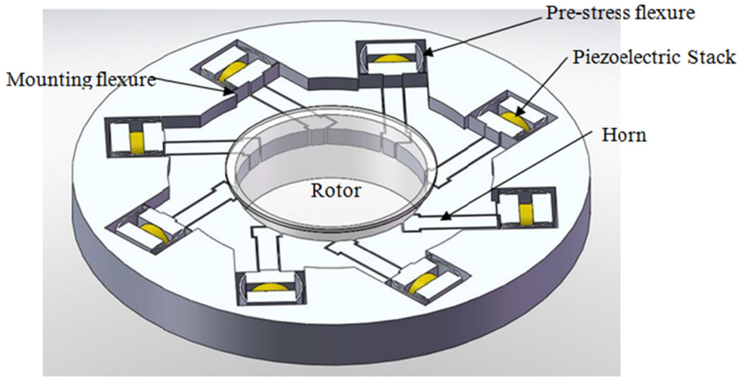


FIGURE 5: A unidirectional rotary motor. The rotor (which is transparent in this view for clarity) is driven by 8 horn actuators and rotates in the clockwise direction.

The motor shown in Figure 5 could be stacked to increase the torque on the rotor or flipped and stacked as shown in Figure 6 to produce bidirectional rotation. To drive the rotor clockwise, it is necessary to excite the horns in the top plate by driving each actuator in resonance. To drive the rotor counterclockwise, it is necessary to excite the horns in the bottom plate by driving each horn in resonance. If the mounting flexure was connected to the backing or an additional stack was implemented between the horn and mounting flexure one could also drive the piezoelectric stack of the inactive plates with a large DC voltage to reduce friction of the inactive plate on the rotor. Otherwise a mechanical lever may need to be employed to reduce the frictional force of the inactive stacks/horns. Bidirectional rotation could also be produce in a single plate by positioning half the horns at an angle to produce an opposing torque. These designs can easily be extended to linear motors as is shown in Figure 7 where we show a motor design that can drive a linear slide in both directions. These designs could also be stacked to increase the blocking force.

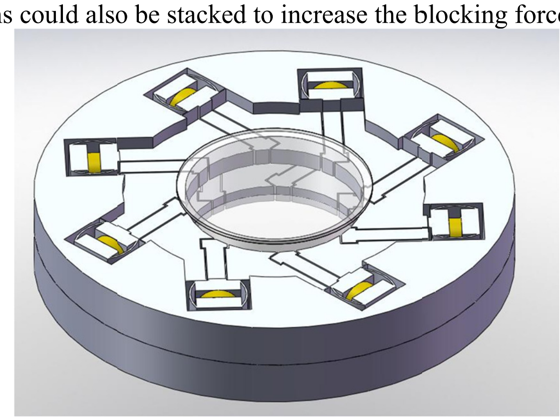


FIGURE 6: A stacked rotary motor with bidirectional drive. To drive the rotor clockwise, it is necessary to excite the horns in the top plate by driving each in resonance. To drive the rotor counterclockwise, it is necessary to excite the horns in the bottom plate by driving each horn in resonance. One could also drive the piezoelectric stack of the inactive plates with a DC voltage to reduce friction of the inactive plate on the rotor.

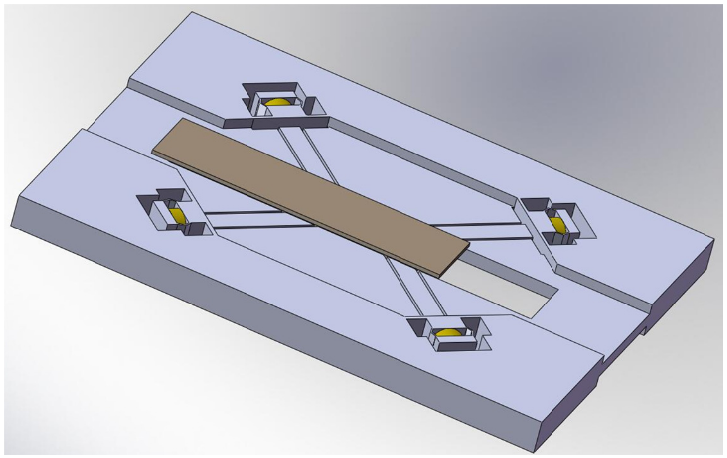


FIGURE 7: A linear motor that drives a slide. Activating the pair of horns on the right pushes the slider to the left and activating the pair on the left pushes the slider to the right.

In addition, the actuator plates may be aligned as shown in Figure 8 to produce multiple axis of rotation. In Figure 8 we show 3 orthogonal axis of rotation however the plates could be orientated in multiple planes at any desired angles. In addition, the surfaces could be curved slightly.

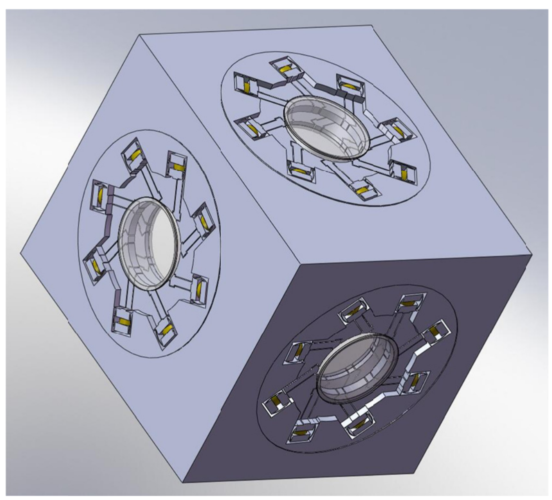


FIGURE 8: A motor with three axis of rotation that are orthogonal. A two axis DOF motor could be used in a manipulator joint.

The piezoelectric rotary and linear motors described in paper are fully scalable. They could be designed to be used in small systems like the motors in electronic cameras or small flight instruments or they could be used to drive large structures like the wheels of a rover or the joints of an instrument deployment device. In addition, if the horn resonance frequency is carefully modeled these motors could be designed to be made extremely quiet [Sherrit et al., 2005]. These motors could be used in many applications that requires motion and need integrated actuation.

3. MODELING

To test the planar motor structures a planar rotary bidirectional motor was designed and modeled using ANSYS. A CAD model and some of the parts of the prototype motor are shown in Figure 9.

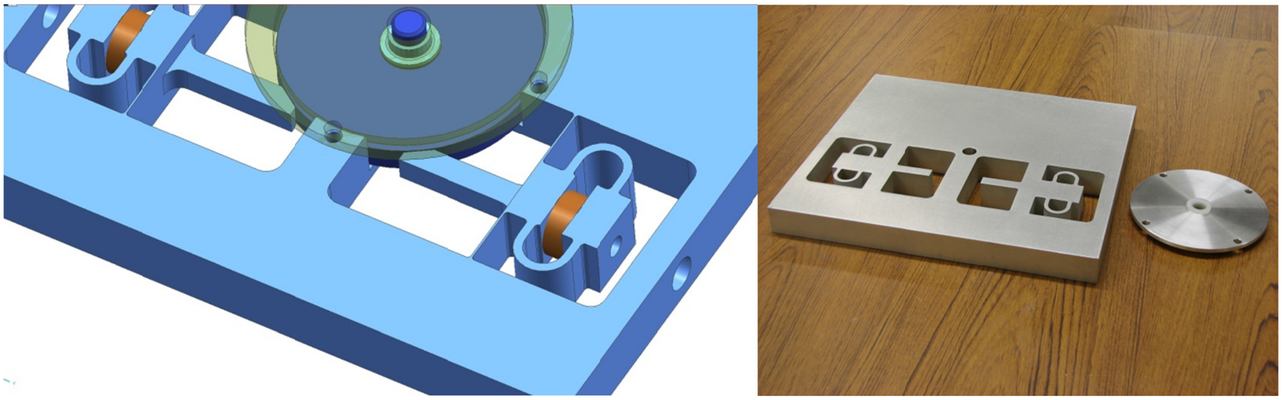


FIGURE 9: A CAD model of a prototype rotary motor that can drives a rotor clockwise and counterclockwise along with a photograph of manufactured parts. The mounting flexure and horn tips still need to be machined in the figure.

The horn actuators of the prototype shown in Figure 9 were modeled in ANSYS to determine the resonance frequency, coupling and the position of the nodal plane. The isolated horn model is shown in Figure 10 and the tip displacement is shown in Figure 11 for two difference mounting flexures shown as red thin structures at the top of the horn base in Figure 10

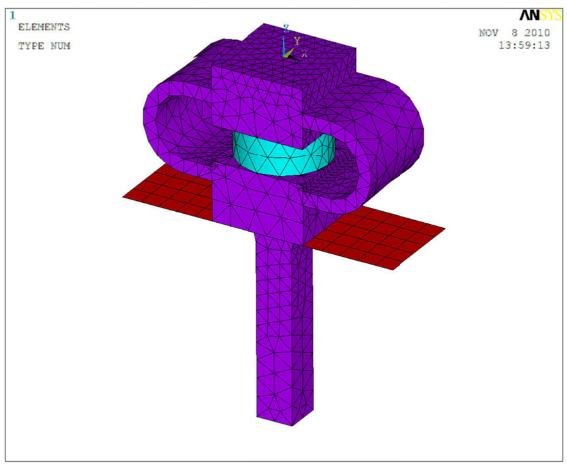
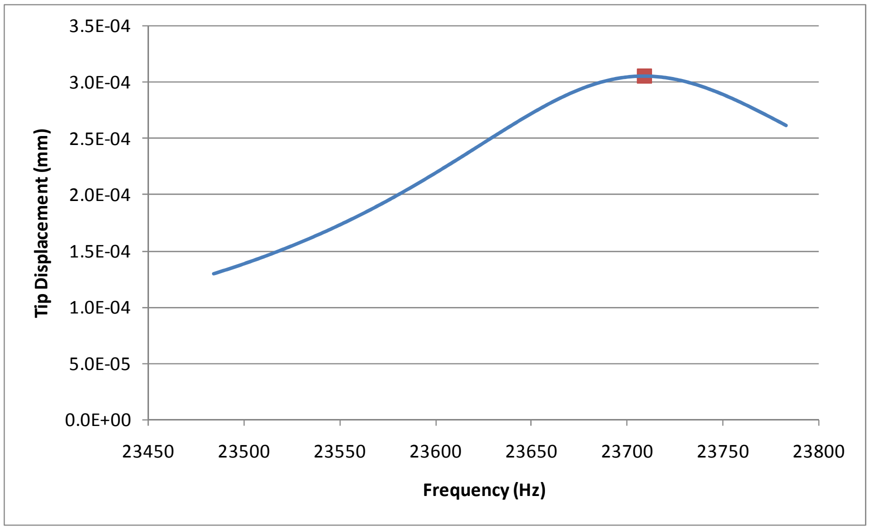


FIGURE 10: The ANSYS model used to model the horn actuators. Total number of nodes= 8753, Total number of elements=5017, Boundary condition: Edges of flexures fixed.

The tip displacement, power and current as a function of frequency was determined for a 1 volt input AC signal and the peak results are show in Table 1.

Table 1. Resonator parameters for two mounting flexure thicknesses at 1 Volt peak excitation. The tip displacement and power and current are amplitude values

Thickness (mm)	0.75	1.5
Resonance f (kHz)	23.6	23.9
Tip displacement (microns)	0.31	0.32
Coupling k (#)	0.20	0.19
Peak power(w)	0.096	0.101
Peak Current (A)	0.104	0.111
Adjacent modes (kHz)	22.9, 24.2	23.3, 24.0



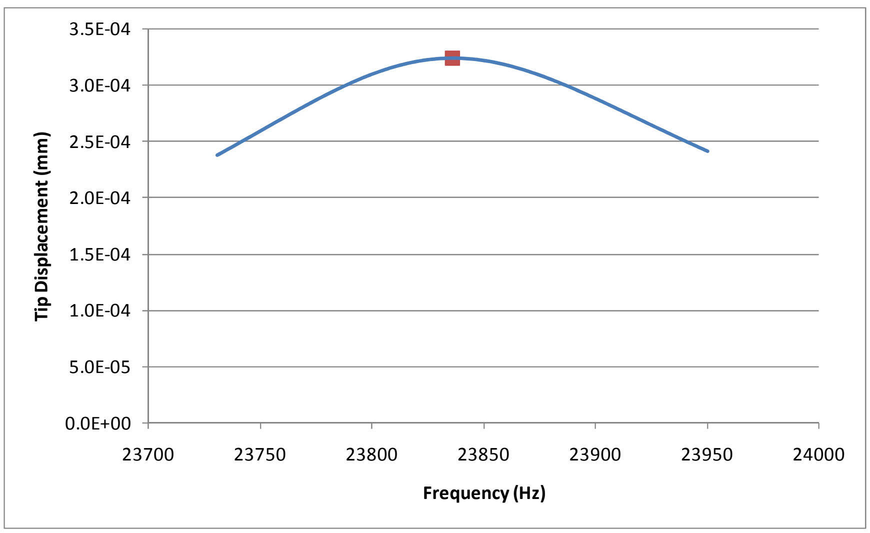


FIGURE 11: The tip displacement amplitude as a function of the frequency from ANSYS for the model shown in Figure 10. The top curve is for a 0.75 mm mounting flexure. The bottom curve is for a 1.5 mm mounting flexure.

The analysis suggests that at 20 volts the theoretical peak tip displacement is about 6 microns and the power dissipated as actuation and heat will be of the order of 40 Watts assuming the displacement is linear in voltage and the power is quadratic in voltage. The speed and torque will be a function of the friction on the rotor and will depend upon the normal forces of the rotor and base and the rotor and the counter driven horn. The rotary motor shown in Figure 9 based on the horn analyzed in Figure 10 with a mounting flexure thickness of 1.5 mm. is currently being fabricated.

4. SUMMARY

In this paper we identified a variety of new approaches that could be used to produce rotation and linear actuation from microscopic deformations at high frequency embedded in structures. The ability to pre-stress the piezoelectric stacks using flexures has allowed for the design of simple shorn structures that can be manufactured using rapid prototyping such as an electron beam melting/manufacturing process (EBM) or EDM. The initial prototype was found during initial testing of the motor with one horn to produce a rotor speed of 15 RPM with a torque of approximately 0.3 N-m. A variety of new designs were presented in which we embedded the horns in planar structures to produce bidirectional and stackable rotary and linear actuation. Initial FEM analysis of the planar horns predicted a resonance frequency of 23.9 kHz with a tip displacement of 6 microns at 20 Volts peak excitation. Prototypes based on our most recent analysis are currently being fabricated.

ACKNOWLEDGMENT

Research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics Space Administration (NASA), and was funded by the Army's RCTA2010 program. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

[1] Sashida T., Kenjo T (1993): An Introduction to Ultrasonic Motors, Claredon Press , Oxford

[2] Ueha S., Tomikawa Y.(1993): Ultrasonic Motors, Claredon Press, Oxford

[3] Uchino K. (1996): Piezolectric Actuators and Ultrasonic Motors (Electronic Materials--Science & Technology, 1), Kluwer Academic Pub; ISBN: 0792398114

[4] Hollerbach J.M., Hunter I.W. Ballantyne J. (1991):"A Comparative Analysis of Actuator Technologies for Robotics." In Robotics Review 2, MIT Press, Edited by Khatib, Craig and Lozano-Perez

[5] Flynn, A. M., Tavrow L.S., Bart S.F., Brooks R.F., Ehrlich D.J., Udayakumar K.R.,Cross L.E. (1992): "Piezoelectric Micromotors for Microrobots" J. of MEMS, **1**, No. 1, pp. 44-51

[6] Barth H.V. (1973):Ultrasonic Driven Motor, IBM Technical Disclosure Bulletin, **16**, pp. 2263

[7] Uchino K. , "Piezoelectric Ultrasonic Motors: Overview", Smart Materials and Structures, **7**, pp. 273-285, 1998

[8] Jin Jiamei, Zhao Chunsheng, " A vibrators alternation stepping ultrasonic motor" Ultrasonics **44**, pp. e565-e568, 2006

[9] CALRAM - http://www.calraminc.com/projects.htm
Downloaded Sept 1st, 2010

[10] RAMCAST- http://www.ramcast.com/ see sub-directory pdf/Ti2%20Conference%20paper.pdf downloaded Sept 1st 2010